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Final Report LDRD 02-ERD-013 Dense Plasma Characterization by X-ray Thomson Scattering

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Final Report LDRD 02-ERD-013

Dense Plasma Characterization by X-ray Thomson Scattering*

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Abstract

We have successfully demonstrated spectrally-resolved x-ray scattering in a variety of dense plasmas as a powerful new technique for providing microscopic dense plasma parameters unattainable by other means. The results have also been used to distinguish between ionization balance models. This has led to 10 published or to be published papers, 8 invited talks and significant interest from both internal and external experimental plasma physicists and the international statistical plasma physics theory community.

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Introduction

The full range of plasmas, from Fermi degenerate, to strongly coupled, to high temperature ideal gas plasmas are present at high density in a variety of laboratory [1-7] and astrophysical environments [8-10]. The Fermi degenerate plasmas can be characterized by $T_e < T_F$, the strongly coupled plasmas by a combination of $T_e > T_F$ and the ratio Γ_{ee} of the Coulomb potential energy between free electrons to the kinetic energy of the free electrons being > 1 , and the ideal plasmas by $\Gamma_{ee} < 1$. These are states of matter occurring at some location during the interaction between intense lasers and a solid and are therefore of general interest for any research program that uses intense lasers. These are also regimes accessed by the DT fuel during an ICF implosion.

Various statistical mechanics models [11-13] differ by factors of several in the predicted electron-ion collisionality in this regime. Material properties such as electrical [14-17] and thermal conductivity [18,19], opacity [20-23], and equation-of-state (EOS) [24, 25] have been studied in this regime to attempt to resolve theoretical and calculational uncertainties. However, the usefulness of such measurements has been impaired because of the lack of an independent measurement of temperature and density. For example, surface probing of any overdense plasmas is difficult to interpret because density gradient scalelengths of the order of $\lambda/2$ dramatically modify observables such as reflectivity and phase modulation. Internal x-ray probing for plasmas at densities near solid and above has relied, so far, on continuum edge spectroscopy and extended x-ray absorption fine-structure (EXAFS), line shape spectroscopy, or non-spectrally resolved x-ray scattering [26-29]. However, the interpretation of results from all

such techniques relies on knowledge of the ionization balance, density and temperature.

By extending the power of spectrally resolved Thomson scattering to the x-ray regime, we have shown by calculating scattering spectra in the random phase approximation that a direct measurement of the ionization state and the temperature of dense plasmas can be achieved. Specifically, by spectrally discriminating between the coherent and Compton-downshifted [30-34] and Doppler-broadened Thomson scattered components, we can gather information on many microscopic parameters, including the free and bound electron densities and fractions, temperature, plasma flow velocity, and plasma collisionality. These direct measurements of microscopic parameters of dense plasmas could eventually be used to properly interpret laboratory measurements of material properties such as thermal and electrical conductivity, EOS and opacity.

X-ray Thomson/Compton Scattering

Incoherent Thomson scattering [35-38] at a probe wavelength λ and angle θ is characterized by the scattering parameter $\eta = \lambda_s/2\lambda\lambda_D < 1$, where $\lambda_s = \lambda/2\sin(\theta/2)$ is the scattering correlation length and λ_D is the plasma Debye correlation length. By switching from current UV lasers near 2400 Å to an x-ray probe at 2.4 Å, we can now probe solid density plasmas with Debye lengths of the order of the interparticle spacing or shorter (1 Å). In Figure 1, the large plasma parameter space available to X-ray scattering at a probe wavelength of 2.4 Å is shown. The gray region denotes the parameter space for the ICF fuel

during compression, reaching super-solid densities. The black regions denote the parameter space for plasmas probed as part of this LDRD research. All of these are in the scattering regime $\eta < 1$, for which spectrally-resolved incoherent Thomson scattering provides direct information on the electron velocity distribution function $f(v)$ of free electrons from the Doppler shifts experienced by scattered probe photons. In particular the width and form of the velocity distribution will in general be a function of both T_e and the Fermi energy T_F , hence also a function of $n_e \sim T_F^{3/2}$.

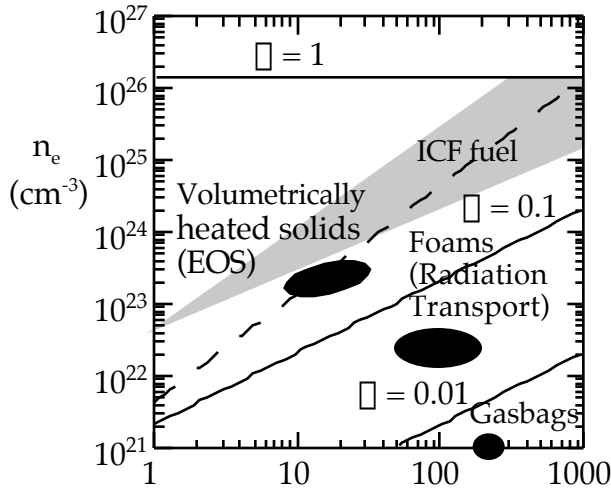


Figure 1: Electron density and temperature parameter space showing plasma regimes accessible. Dashed line denotes $T_e = T_F$ boundary. Solid lines give scattering parameter for $\eta = 180^\circ$ Thomson scattering for $\lambda = 2.4 \text{ \AA}$ probe. Black regions denote plasmas already probed. Gray region denotes ICF fuel regime to be explored in future.

Results and Summary

Over the three year LDRD grant, we have developed at the Omega facility various isochorically heated uniform high density low Z plasmas that are probed by closely-coupled x-ray line radiation sources [IV, VI], for which the near backscattered x-rays are resolved by high efficiency spectrometers [IX]. In parallel, we have developed an integrated theoretical framework for analyzing the scattered spectra for extracting ionization state and electron temperature [I], [II], [III]. The results have been used to distinguish between ionization balance

models [VI], [VII], [VIII] for Be and C, and the ionization state and temperature of radiatively heated C foams and CH gasbags [X]. The success of this project has led to a further funded LDRD on using forward collective scattering ($q > 1$) to probe solid density plasmons, and to proposals for scattering using future free-electron x-ray lasers [V]. Other groups around the world are now beginning to apply this technique to measure the adiabat of ICF ablators and eventually to measure the ionization balance of shocked D_2 , an important outstanding experimental issue. Finally, we have designed experiments for applying x-ray scattering to measuring the adiabat of imploded DT ICF fuel at NIF that can reach 100x solid densities. These latter experiments would use a PW beam on NIF to create 50 keV $K\alpha$ x-rays for probing hot imploded cores.

Publications resulting from this LDRD:

I) G. Gregori, S.H. Glenzer, et. al., "Calculations and Measurements of X-Ray Thomson Scattering Spectra in Warm Dense Matter", in Proceedings of 16th International Conference on Spectral Lineshapes, C.A. Back Ed., (AIP Press, New York, 2002) pp. 359-368. **UCRL-JC-148076**

II) G. Gregori, S.H. Glenzer, W. Rozmus, R.W. Lee, and O.L. Landen, "Theoretical Modelling of X-Ray Scattering as a Dense Matter Probe", Phys. Rev. E **67** (2003) 026412. **UCRL-JC-147395**

III) G. Gregori, R.W. Lee, S.H. Glenzer, and O.L. Landen, "Strong Coupling Corrections in the Analysis of X-Ray Scattering Measurements", J. Phys. A **36** (2003) 5971. **UCRL-JC-150760**

IV) S.H. Glenzer, G. Gregori, R.W. Lee, F.J. Rogers, et. al., "Demonstration of Spectrally Resolved X-Ray Scattering in Dense Plasmas", Phys. Rev. Lett. **90** (2003) 175002. **UCRL-JC-149694-Rev1**

V) R.W. Lee, S.J. Moon, H.K. Chung, W. Rozmus, H.A. Baldis, G. Gregori, R.C. Cauble, O.L. Landen, J.S. Wark, A. Ng, S.J. Rose, C. L. Lewis, D. Riley, J.-C. Gauthier, P. Audebert, "Finite Temperature Dense Matter Studies on Next Generation Light Sources," Opt. Soc. Amer. **20** (2003) 770. **UCRL-JC-147883-Rev1**

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X) G. Gregori, S.H. Glenzer, H.-K. Chung, R.W. Lee, N.B. Meezan and O.L. Landen, "Measurement of the Ionization Balance in High Temperature Plasma Mixtures by Temporally Resolved Scattering", to be published in J. Quantit. Spectrosc Radiat Trans (2005). **UCRL-JRNL-208894**

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